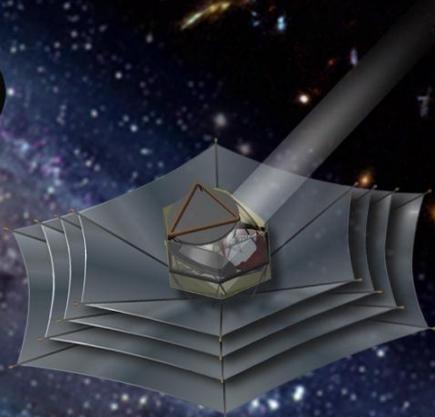


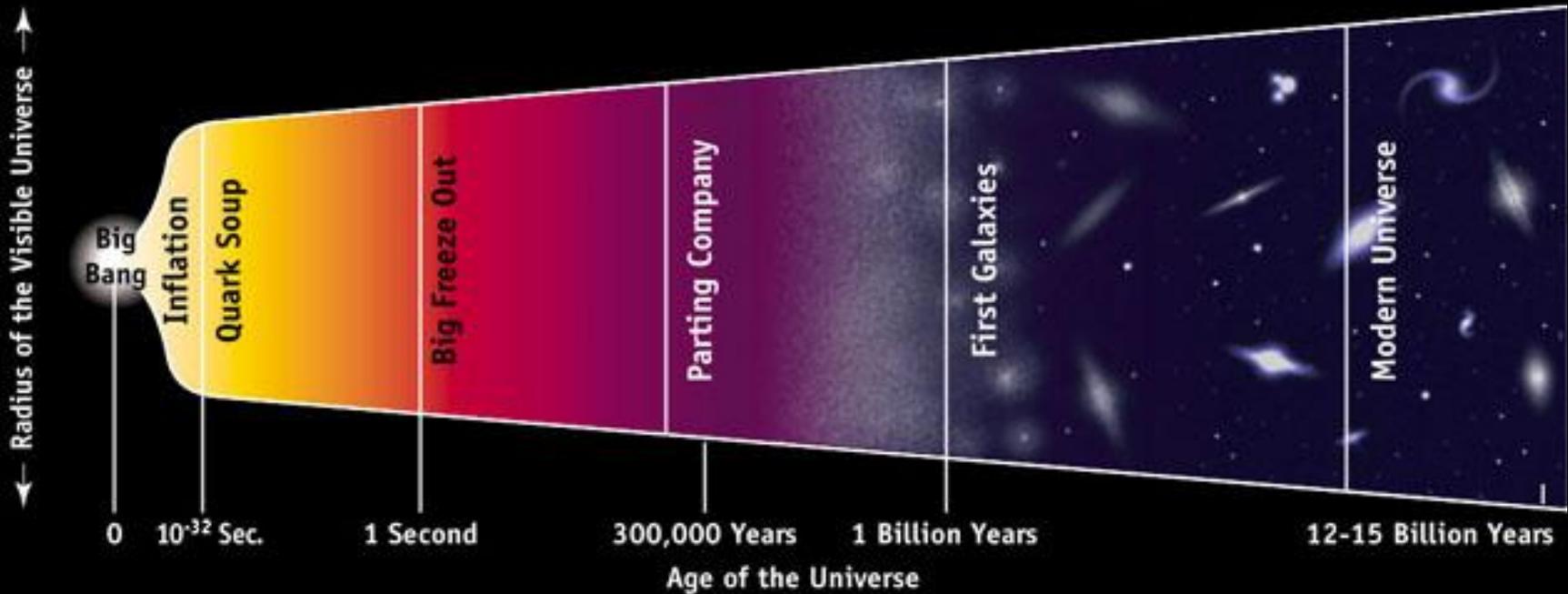
# The Inflation Probe Science Interest Group

Jamie Bock (Caltech/JPL)



PhysPAG Meeting, HEAD @ Chicago 19 August 2014

# Testing Inflation with CMB Polarization



## Key Inflationary Observables

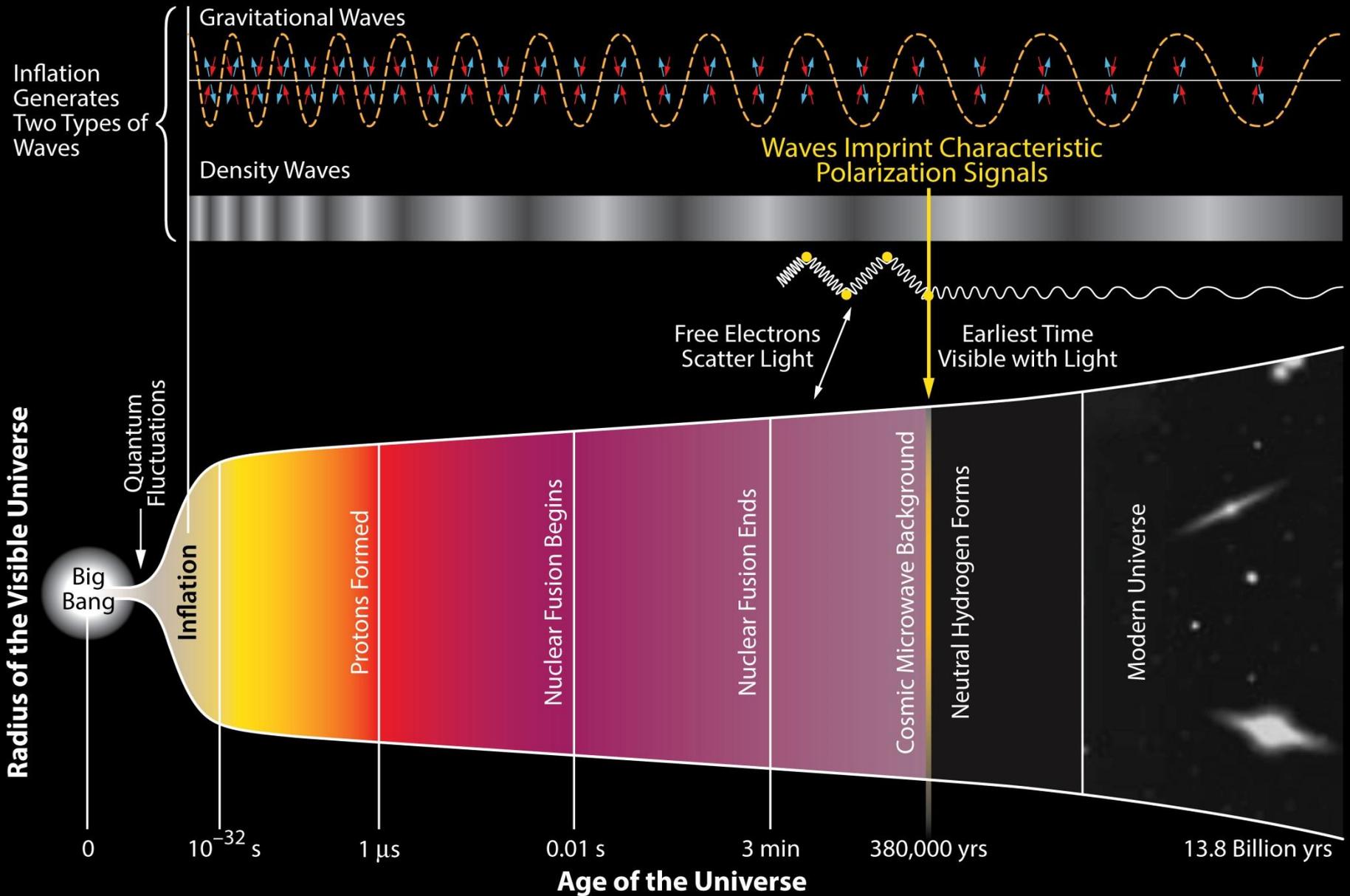
1. Nearly scale-invariant fluctuations
2. Flat universe
3. Adiabatic fluctuations
4. Nearly Gaussian fluctuations
5. Super horizon fluctuations
6. Departure from scale invariance
7. Non-Gaussianity?
8. Running of the spectral index?
9. **Inflationary gravitational waves?**

## First Definitive CMB Result

- COBE  
Boomerang + Maxima + TOCO  
Boomerang + Maxima + WMAP  
WMAP  
WMAP  
Planck  
Planck  
Planck + BAO  
**Inflation Probe**

***Comprehensively measure inflationary CMB polarization signal corresponding to inflation at GUT energy scales***

# History of the Universe

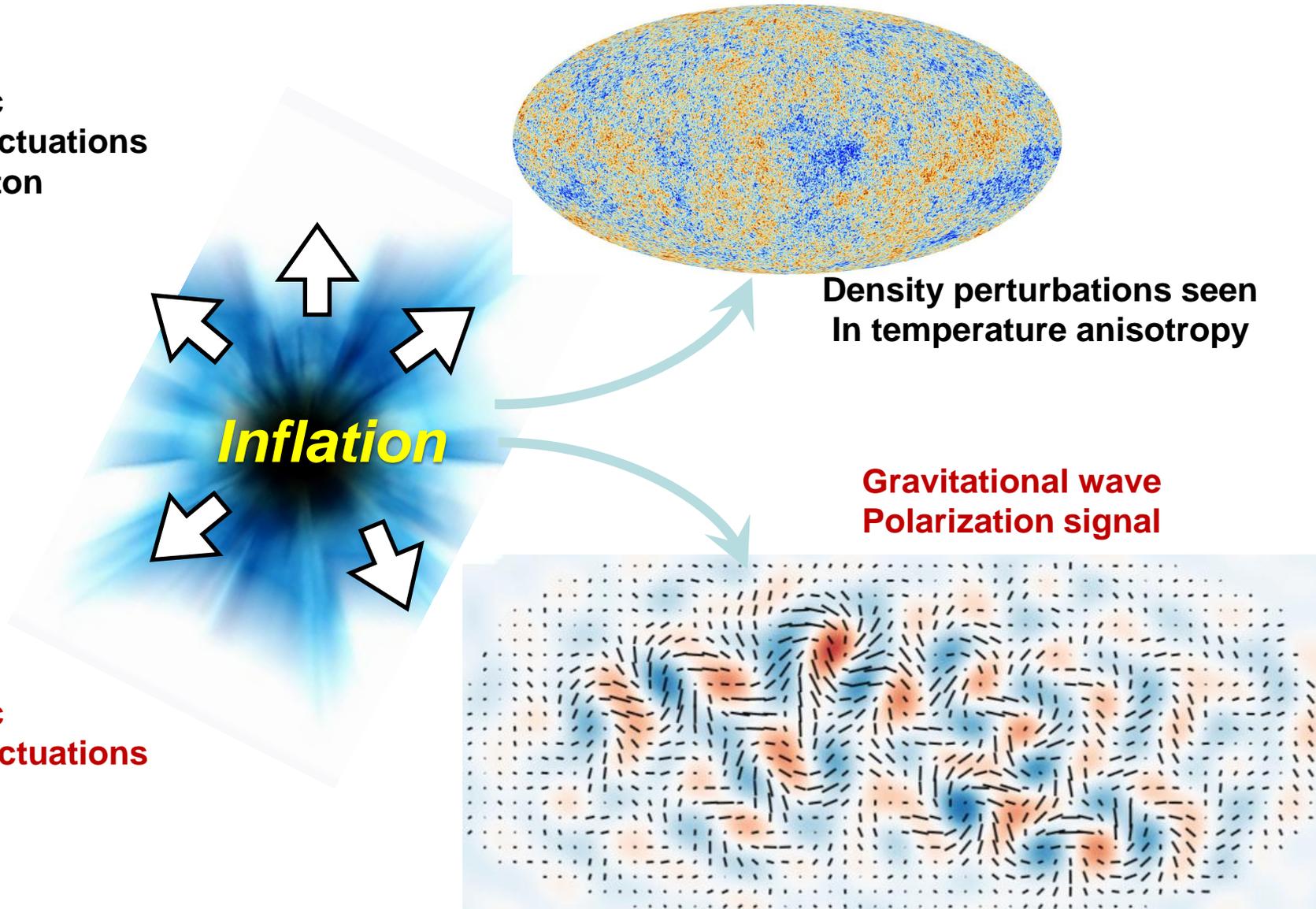


# Density perturbations and gravitational waves

Sub-atomic vacuum fluctuations of the inflaton

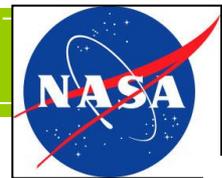


Sub-atomic vacuum fluctuations of graviton

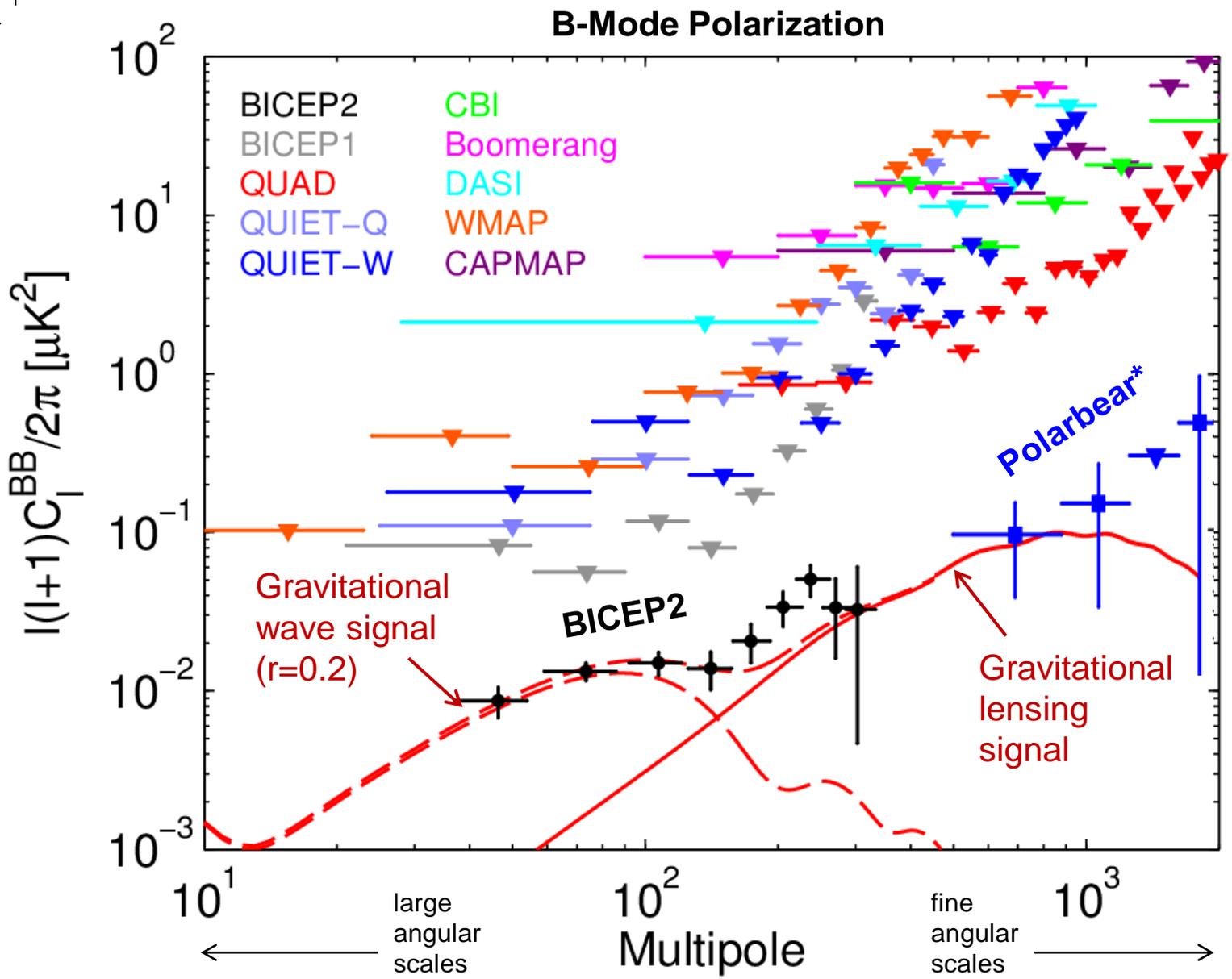


Density perturbations seen in temperature anisotropy

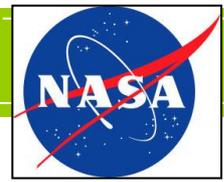
Gravitational wave Polarization signal



# Current State of CMB Polarization Measurements



\*Lensing signal also detected by SPT and Polarbear in cross-correlation with *Herschel* map



# IPSIG White Paper on CMB Planning

## Phase 1: Determine origin of BICEP2 signal

- Determine CMB and Galactic components by a multi-band analysis
- Should match predicted CMB angular spectrum
- Should satisfy statistical isotropy
  - Planck + BICEP2 soon
  - Coming sub-orbital and ground-based measurements
  - If there is a CMB component, then pursue steps 2-3

## Phase 2: Precision measurements of $r$

- Precise measurements of inflation parameters distinguish between models
  - Requires covering more sky and higher sensitivity
  - May be done with a satellite in phase 3

## Phase 3: Measure B-mode spectrum to astrophysical limits

- Measure from lowest to highest accessible spatial modes
- Precise determination of  $r$  and theory angular spectrum
- Consistency test between tensor and scalar index
  - All-sky multi-band measurement requires a satellite

# The *Planck* Satellite

The *definitive* CMB survey for the immediate future

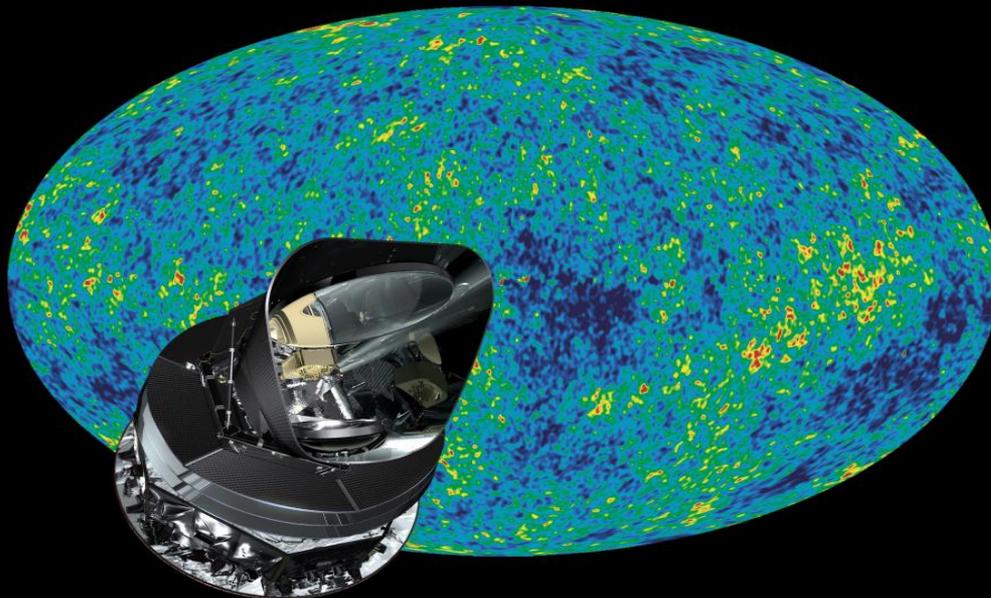
- A cornerstone for cosmology
- Priors for Euclid + WFIRST

Unprecedented maps of Galactic emission

- Used in every new CMB experiment
- Key for planning the inflation probe

A wealth of astrophysics

- SZ clusters
- Extragalactic sources
- Extragalactic background map
- Cold Galactic sources
- And much more!



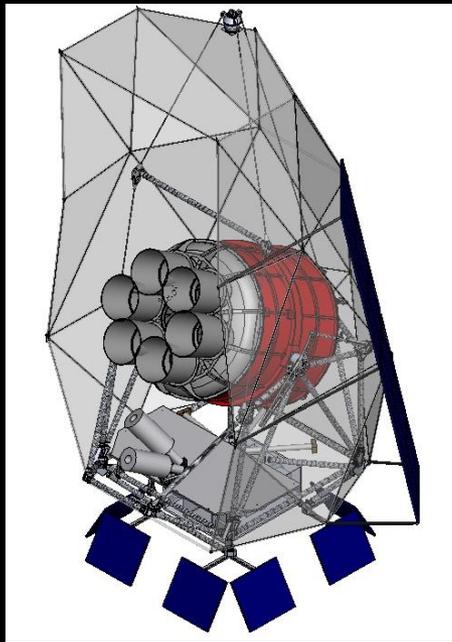
## Planck Strengths

- Comprehensive temperature measurements
- 9 bands for foregrounds separation
- Excellent polarization sensitivity
- All-sky coverage

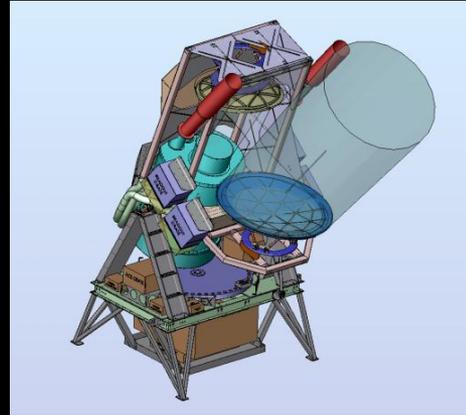
## Planned Data Releases

- March 2013      CMB Temperature
- October 2014    CMB Polarization #1
- December 2015   Final Data Release

# Sub-Orbital and Ground-Based Program



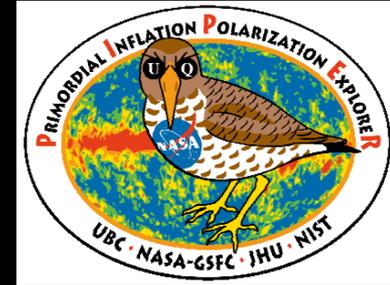
**SPIDER**



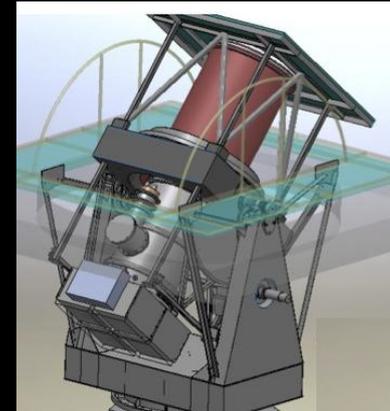
**EBEX**



**POLARBEAR**



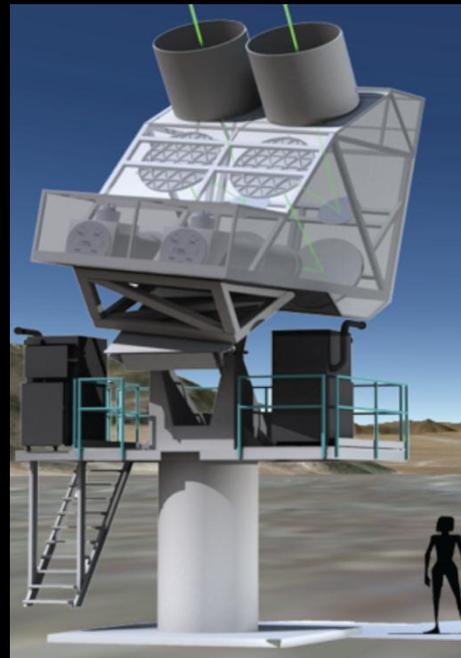
**PIPER**



**BICEP3**



**BICEP2 / KECK**



**CLASS**



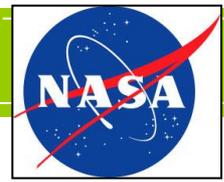
**SPT-POL**



**ACT-POL**

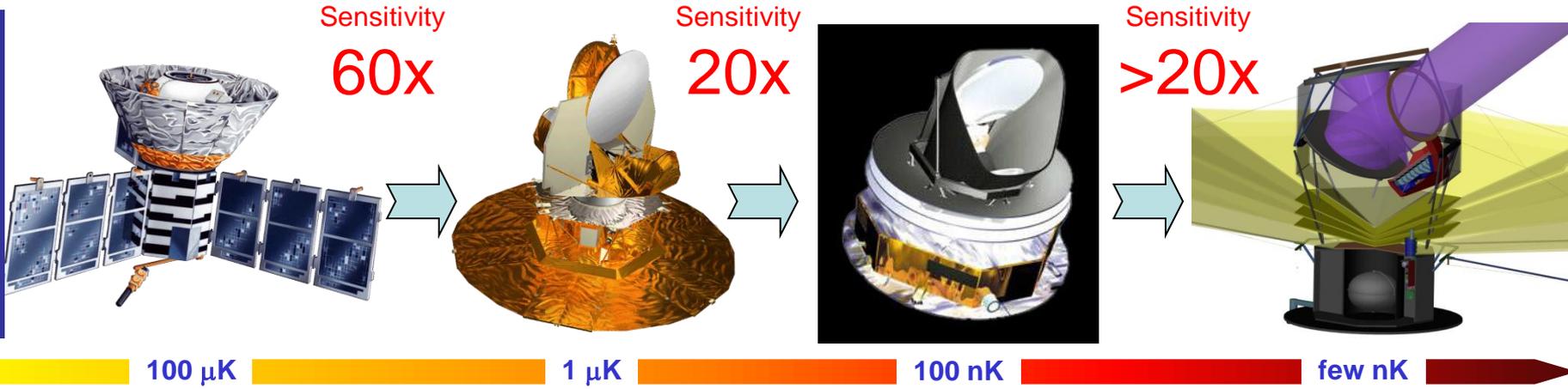


**ABS**



# Technologies to Space: A Proven and Cost-Effective Path

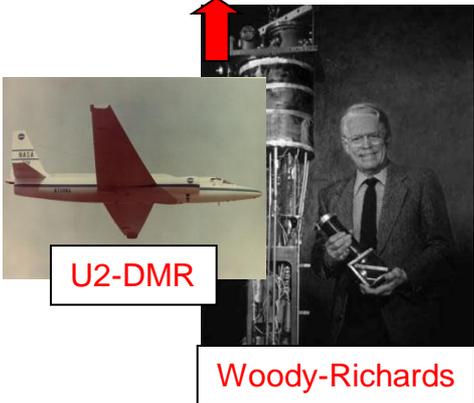
Satellite Mission



Sub-Orbital Precursor

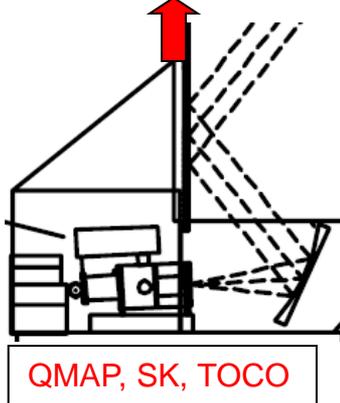
**COBE**

1989



**WMAP**

2001



**Planck**

2009



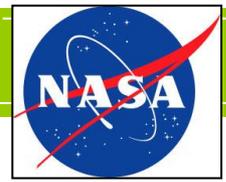
**Inflation Probe**

2020+

Multiple  
Ground-based  
&  
Balloon-borne

## Historical Interplay: Suborbital Experiments serve to

- Shape scientific objective of a space mission
- Train leaders of future orbital missions
- Develop experimental methodologies
- Develop technologies at systems level

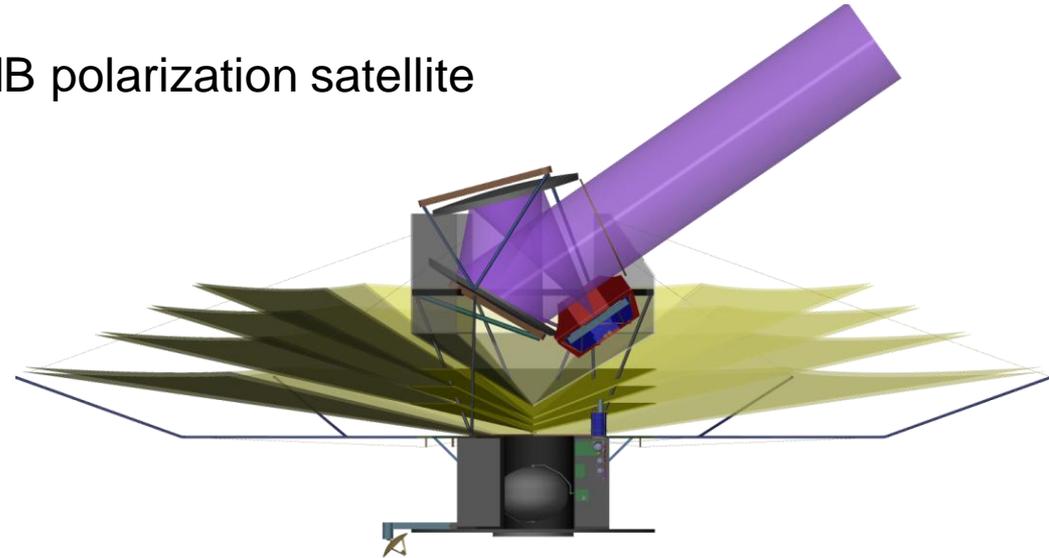


# The Inflation Probe SIG

Organizers: Jamie Bock and Shaul Hanany  
Membership: All interested and contributing individuals

Objective: Preparing for a future CMB polarization satellite

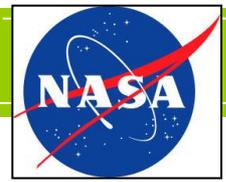
- US planning for a 2020s mission
- European M4 opportunity
- Japanese LightBird mission
- US 2017 MIDEX opportunity



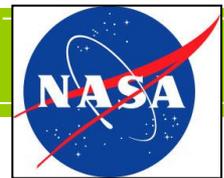
US 2009 EPIC Mission Concept

## Recent Activities

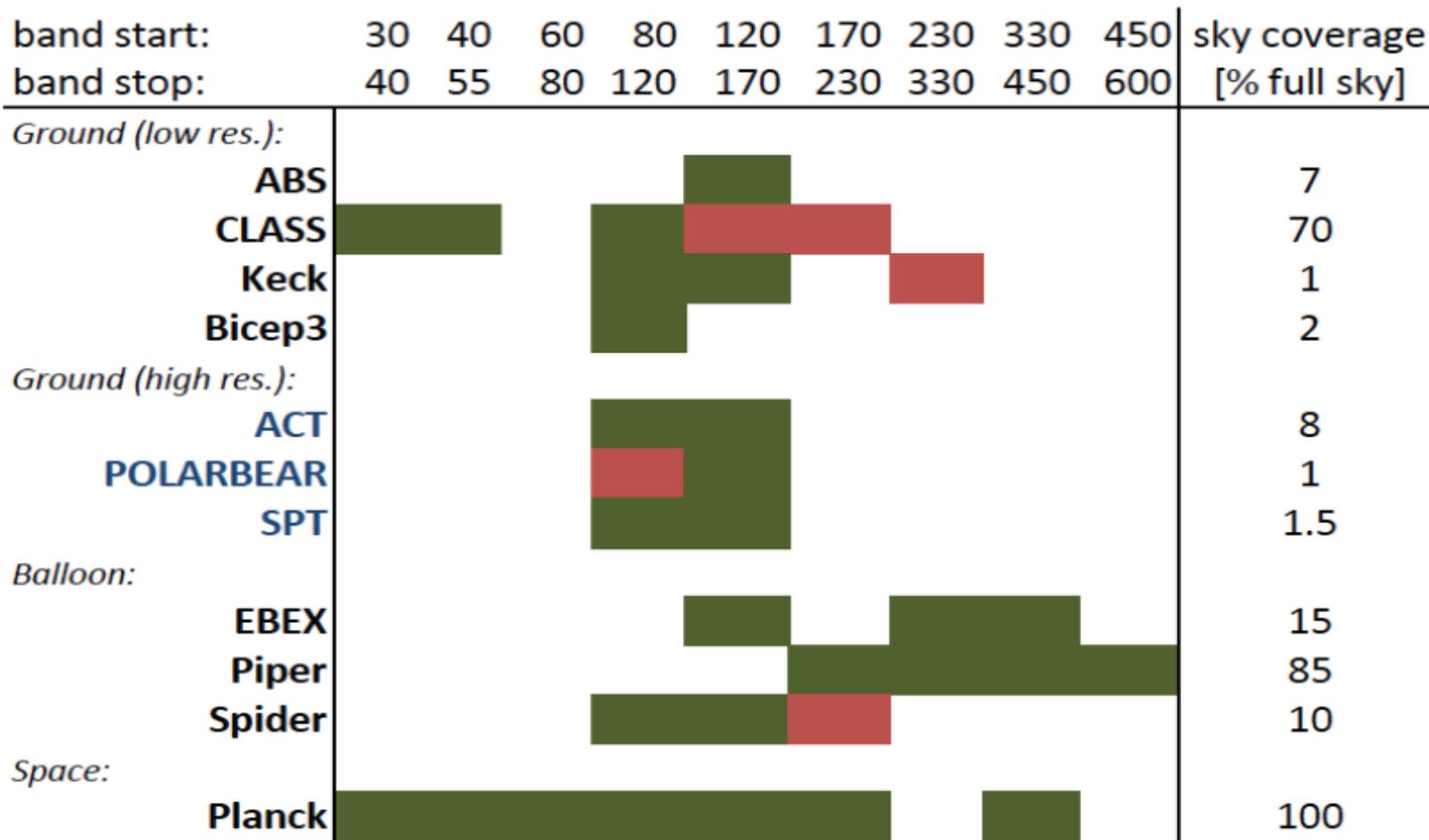
CMB Planning Workshop Minneapolis	14-17 January 2015
White Paper on CMB Planning to NASA	August 2014
Letter of Concern on Planck Legacy Analysis	August 2014
Gap technologies for the Inflation Probe	July 2014
Roadmap for CMB Technology Development	September 2011

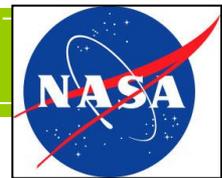


Backup



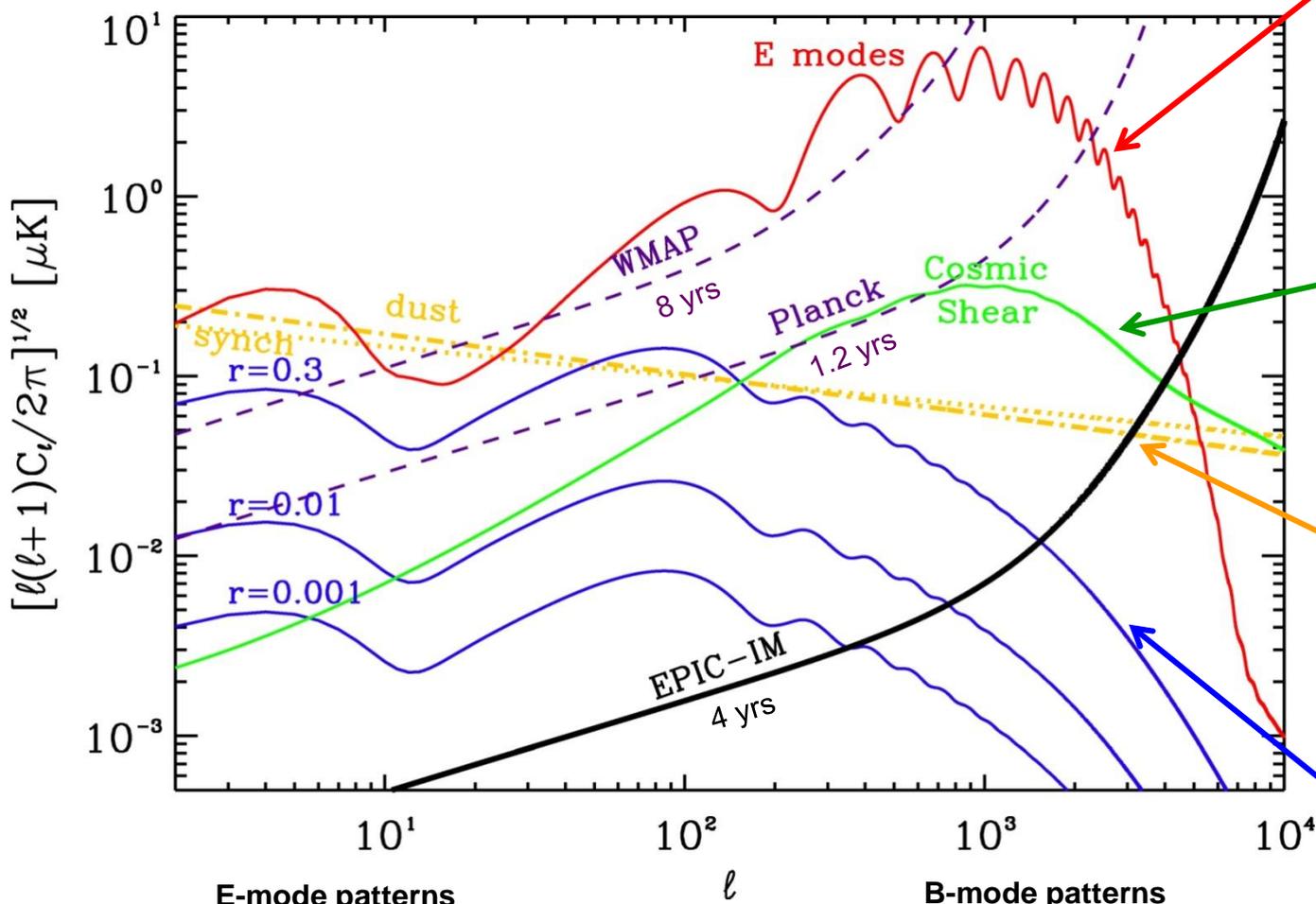
# Coming Experiments





# CMB Polarization Science is Deep and Broad

## CMB Polarization Spatial Power Spectra



**Scalar Perturbations**  
*E-modes*

- Precision cosmology
- Departure from scale inv.
- Reionization history

**Gravitational Lensing**  
*B-Modes*

- Neutrino mass hierarchy
- Dark energy at  $z > 2$

**Galactic Magnetic Fields**  
*E & B-Modes*

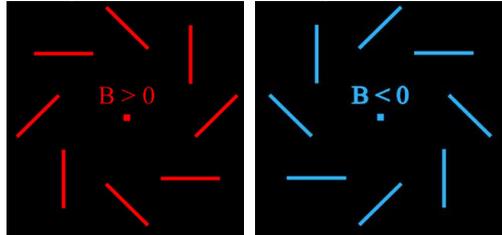
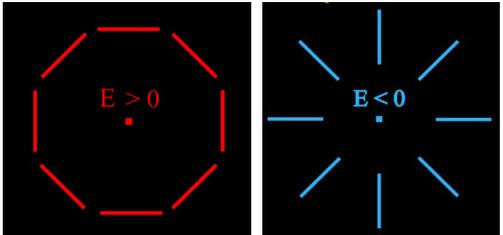
- Star formation
- Large-scale fields

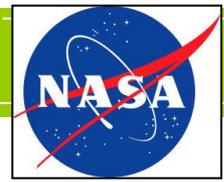
**Inflationary**  
**Gravitational Waves**  
*B-modes*

- GUT energy scale
- Large field inflation
- $n_t / r$  consistency test

E-mode patterns

B-mode patterns





# Inflation Probe Technology Development

## Priorities from the Inflation Probe Technology Roadmap

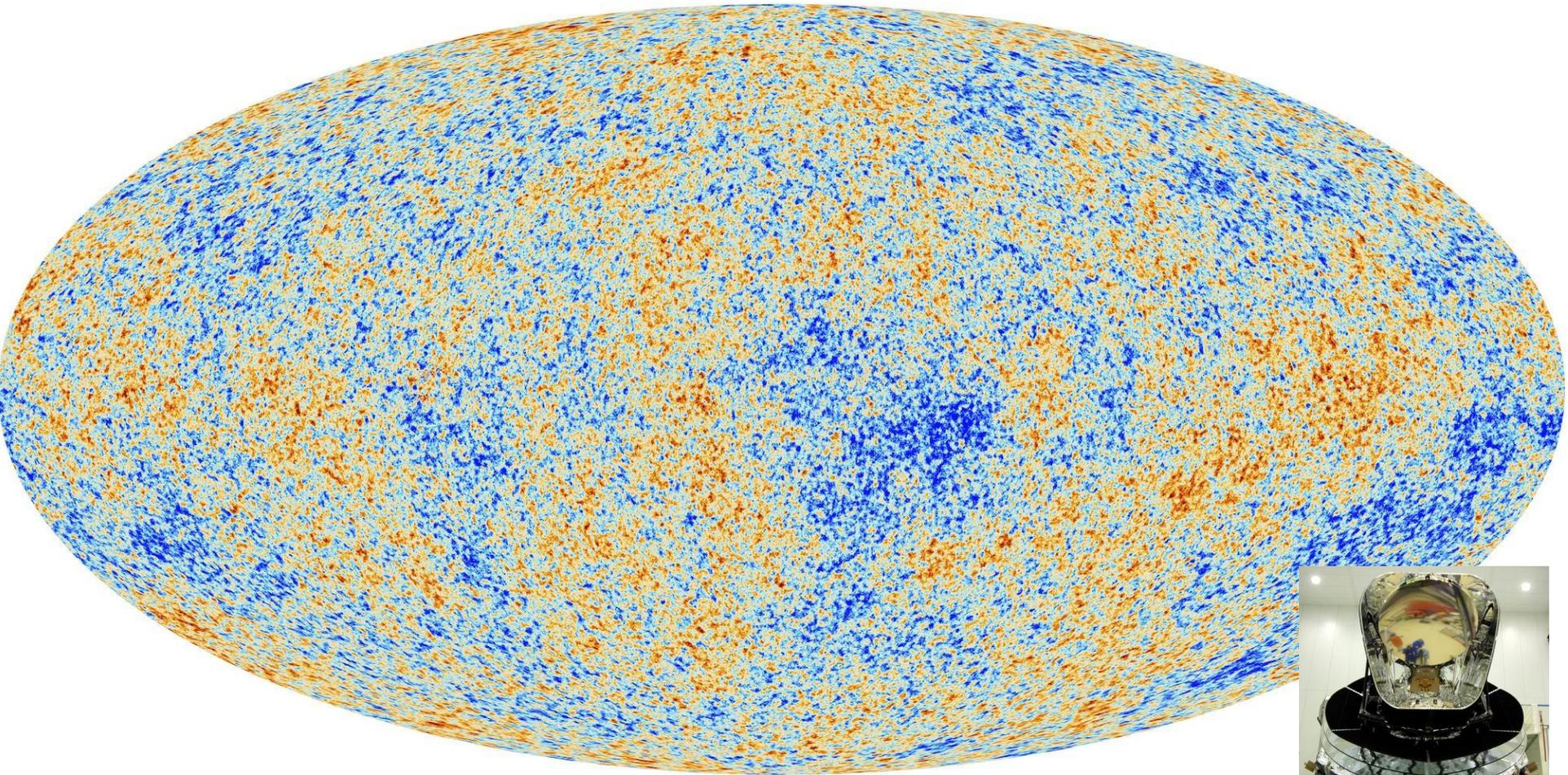
Technology	Priority	Timescale	Candidates	TRL
Detector Arrays	High	Sub-orbital experiments	TES+SQUID+Antenna HEMT / MMIC	4-5
Optics	Medium	Sub-orbital experiments	Polarization modulators AR coatings	2-5
Coolers	Low	Develop for space	Passive+mechanical+sub-K	3-9
Advanced Arrays		Develop for simplified space implementation. Connects to X-ray, far-IR and optical astronomy	MKID+RF resonator TES+RF resonator	3

### Community Technology Plan

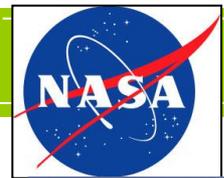
- Very directed: 4 technologies
- Effective: implement in sub-orbital and ground-based experiments
- Cross-cutting: overlap with X-ray and far-infrared needs
- Prioritization: clearly described

# Cosmic Microwave Background

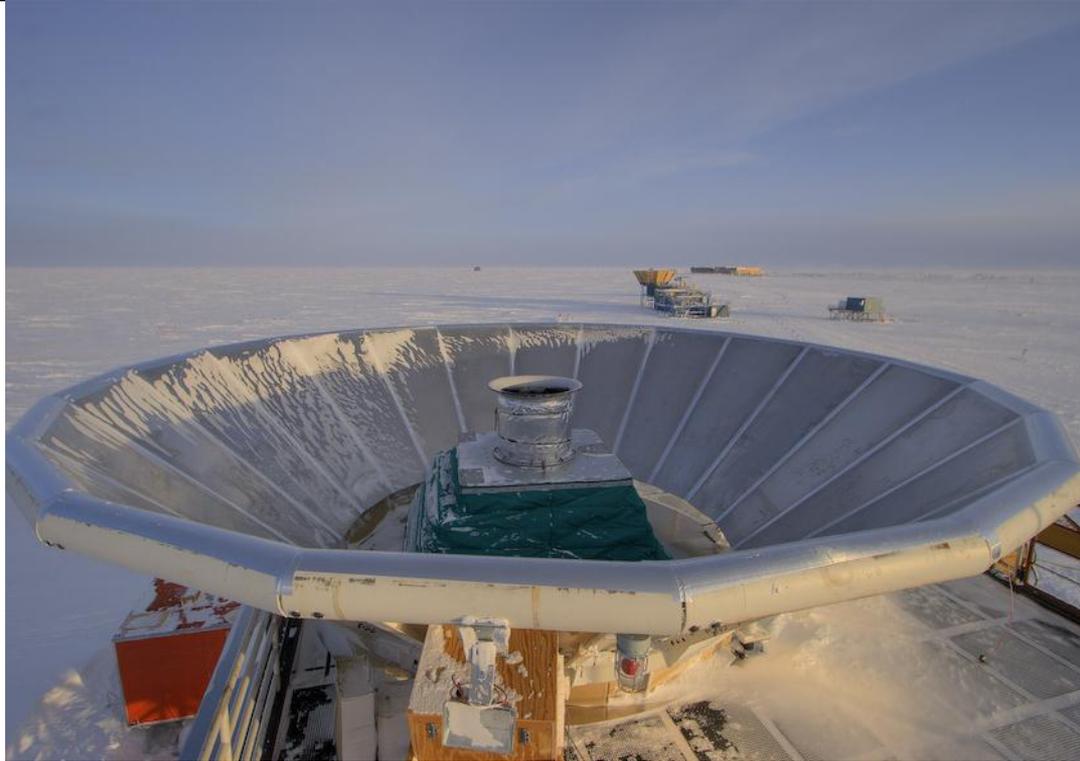
*Our best probe of inflation*



The Planck Satellite



# Multi-Frequency Data: BICEP2 & Planck



BICEP2 + Keck Array



ESA Planck Satellite

- **BICEP2/Keck** and **Planck** combined gives unprecedented *sensitivity* and *frequency coverage* to separate CMB and Galactic emission
- Multiple tests also coming from sub-orbital and ground-based experiments